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THE APPLICATION OF MODELING AND OPERATIONS RESEARCH TECHNIQUES TO DRINKING WATER SYSTEMS

by

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16. ABSTRACT

Mathematical modeling and operations research techniques are used to optimize the various subsystems that make up the total urban water system. An example is given using branch and bound techniques for locating granular activated carbon regeneration sites and for defining optimal regional configurations. The results of this analysis indicate that regional facilities can provide a least-cost solution for small water utilities faced with the need to reactivate carbon.

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THE APPLICATION OF MODELING AND OPERATIONS RESEARCH TECHNIQUES TO DRINKING WATER SYSTEMS

by

Robert M. Clark[1] and Jeffrey Q. Adams[2]

ABSTRACT: Water supply sytems are generally composed of: (1) collection works; (2) purifications works, where needed; and (3) transportation and distribution systems. The collection works either tap a source of water that is adequate in quantity to satisfy present and reasonable future demands on a continuous basis, or they convert an intermittent source into a continuous supply by storing surplus water for use during periods of low flows. If the water is not of satisfactory quality at the point of collection, purification works treat it, e.g., polluted water is disinfected; esthetically unattractive or unpalatable water is treated to make it attractive and palatable; water containing iron or manganese is subjected to deferrization or demanganization; corrosive water is stablized chemically; and excessively hard water is softened. The transportation and distribution works convey the collected and treated water to the community, where it is distributed to the consumers. The total urban water works systems involves large investments in both operating and capital funds.

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EPA's Drinking Water Research Division has applied mathematical modeling and operations research techniques, in order to optimize various subsystems that make up the total urban water system. Examples of these applications include:

- Branch and bound models for locating regional granular activated carbon regeneration sites
- Simulation models for evaluating the tradeoff in cost and performance of drinking water unit processes designed to meet a specified set of maximum contaminant levels.
- Use of cost and performance models for predicting optimal design of full-scale granular activated carbon and air-stripping systems.
- Proportional hazards models for predicting break and repair events in drinking water distribution networks.
- Hydraulic and chemical reaction kinetics models for predicting water quality in distribution networks.
- Water quality models for predicting downstream water quality from upstream discharges.

This paper will develop an example using branch and bound techniques for locating granular activated carbon regeneration sites and for defining optimal regional configurations. The results of this analysis indicate that regional facilities can provide a least cost solution for small water utilities faced with the need to reactivate carbon.

KEY WORDS: BRANCH AND BOUND; COMPUTERS; ECONOMIC ANALYSIS; GRANULAR ACTIVATED CARBON; MATHEMATICAL MODELS; OPTIMIZATION; REGIONAL PLANNING; REGIONAL REACTIVATION; WATER SUPPLY

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INTRODUCTION

Water supply systems are generally composed of: (1) collection or acquision works; (2) purification or treatment works where needed; (3) delivery or transportation and distribution systems; and (4) support services or management functions.

Collection or acquistion works either tap a source of water that is adequate in quantity to satisfy present and reasonable future demands on a continuous basis, or they convert an intermittent source into a continuous supply by storing surplus water for use during periods of low flows. If the water is not of satisfactory quality at the point of collection, the water is purified or treated, e.g., polluted water is disinfected; esthetically unattractive or unpalatable water is treated to make it attractive and palatable; water containing iron or manganese is subjected to deferrization or demanganization; corrosive water is stabilized chemically; and excessively hard water is softened. Delivery of transportation and distribution works convey the collected and treated water to the community, where

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it is distributed to the consumers. The support service function includes management items normally included in the accounting term "overhead" such as meter reading and other management related activities. Figure 1 is a schematic diagram that illustrates these functions.[1] The total urban water works systems involves large investments in both operating and capital funds. It is estimated that there are nearly 60,000 community water supplies in the U.S. (serving 25 connections or more) and that 6 billion dollars a year is spent on the water supply service function.[2]

Not be be overlooked with regard to water supply is the responsiblity to provide preventive public health protection. Although there are virtually no waterborne disease outbreaks from typhoid in this country, occasional outbreaks from less harmful Giardia are a reminder that this preventive public health function is still important.

Despite the size and importance of the municipal water supply activity in the U.S., there is little systematic application of operations research techniques to the industry. The authors have conducted a thorough although not exhaustive literature review and have found relatively few citations in the literature that illustrate the application of classical operations research (OR) techniques to water supply systems.

In the following sections some representative examples of OR techniques applied to water supply will be discussed. A brief summary of the activities of EPA's Drinking Water Research Division in modeling and systems analysis will be presented and finally a more traditional OR application of a branch and bound algorithm to a facility location problem in water supply will be examined. The facility location problems deals with the allocation of capacity for granular activated carbon reactivation on a regional basis.

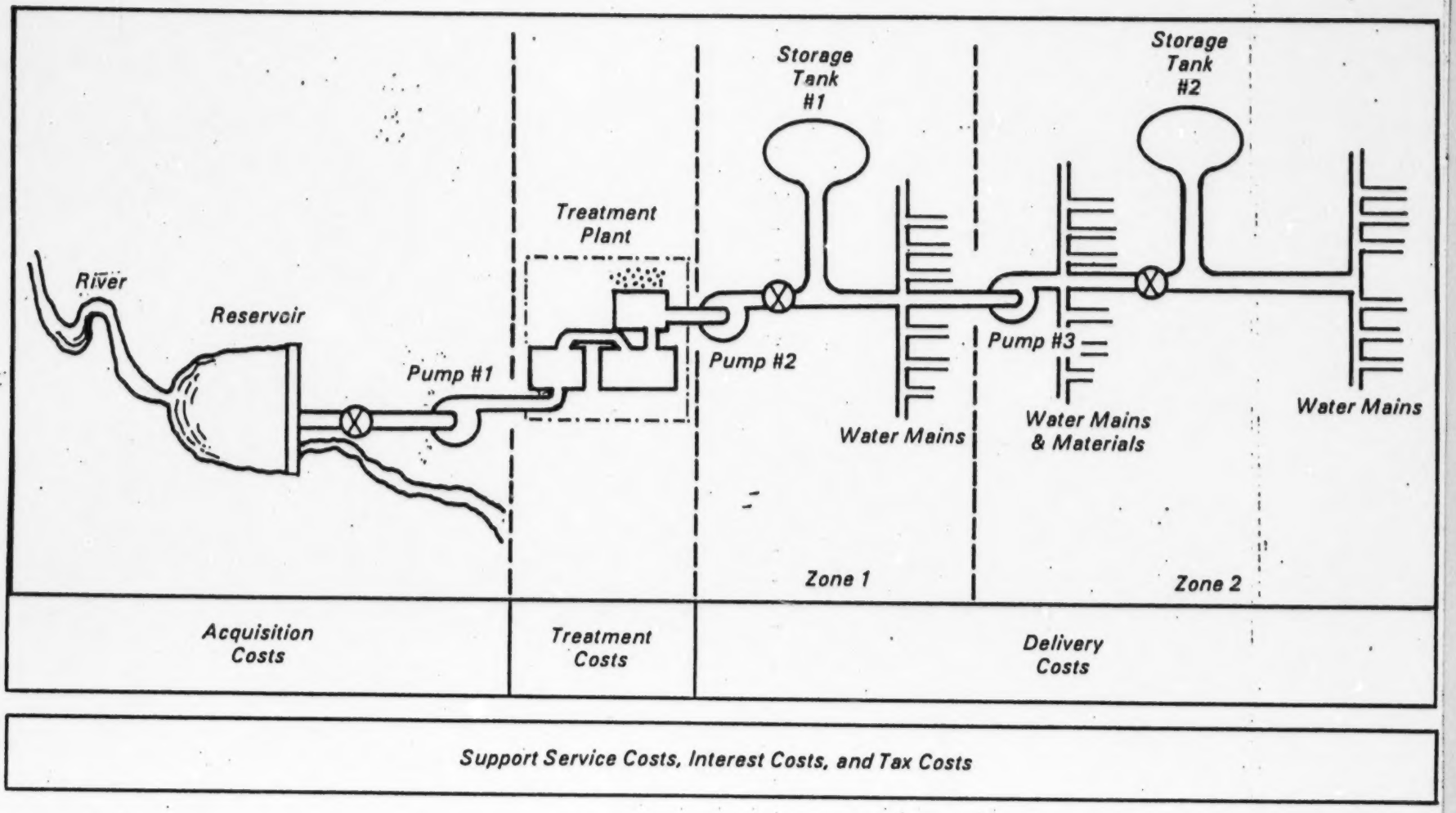

Figure 1. Simplified schematic of a typical water utility.

Granular activated carbon is a technique that is very useful for removing trace quantities of many types of organic compounds from water.

OR APPLICATIONS IN WATER SUPPLY

The following discussion will be structured around the schematic concept shown in Figure 1. Each of the functions will be examined and illustrative examples associated with this function will be presented.

ACQUISITION

Little literature is to be found that shows the direct application of operations research to the acquisition function. Although there is a large body of literature related to the application of OR to water resource systems and reservoir design.

TREATMENT

A few citations can be found in the literature that show the application of OR techniques to treatment processes. Wanielista published a Ph.D thesis in 1971 using integer programming to find minimum cost designs for various combinations of unit processes.[3] He described the concave cost functions in terms of piecewise linear functions. Muhich conducted a study of optimal capacity expansion for water treatment as part of his Ph.D work at Harvard University.[4] More recently O'Melia published a fairly sophisicated article in which he studied the relationships among raw water quality pretreatment facilities and the design of packed bed filters. O'Melia found that particle size, particle concentration, particle surface characteristics and solution chemistry in the raw water supply have important and predictable effects on filter design.[5]

DELIVERY

Delivery (transportation and distribution) systems have been studied most extensively of all of the water supply functions with respect to application of OR techniques. Typical of these studies was a paper by Rasmusen that suggested a technique for optimizing water supply distribution networks.[6] A heuristic procedure for optimization of water supply networks is presented.

Deb has developed a hydraulic network analysis to find a workable optimum cost solution of pipe sizes for various branches of the network for known nodal hydraulic heads and outflows, incorporating a pipe cost function.[7] Using cost functions for a pumping station and an elevated water service reservoir the total cost of a distribution system has been solved for various inlet hydraulic heads, pressure surface parameters, and reservoir positions. The effect of the density of population on the cost has been studied, and a general computer program developed.

Walski has developed a useful summary of the state-of-the-art of hydraulic modeling. Various approaches to optimizing hyraulic systems are presented.[8]

Shamir discusses the expansion and/or modification of an existing system. Those pipes, pumps, and values which are to remain unchanged are easily introduced into the model, as fixed values, and are not allowed to change.[9]

Karaa and Marks have developed heuristic techniques for planning and locating facilities under various demand conditions. The techniques deal with the use of concave functions.[10]

SUPPORT SERVICES

Litte or nothing has been done to apply OR techniques to this water supply function.

DWRD ACTIVITIES

EPA's Drinking Water Research Division has initiated the following activities related to modeling and operations research techniques as applied to water supply:

- Branch and bound models for locating regional granular activated carbon regeneration sites
- Simulation models for evaluating the tradeoff in cost and performance of drinking water unit processes designed to meet a specified set of maximum contaminant levels.
- Use of cost and performance models for predicting optimal design of full-scale granular activated carbon and air-stripping systems.
- Proportional hazards models for predicting break and repair events in drinking water distribution networks.
- Hydraulic and chemical reaction kinetics models for predicting water quality in distribution networks.
- Water quality models for predicting downstream water quality from upstream discharges.

In the following section an example using a branch and bound techniques for locating granular activated carbon regeneration sites and for defining an optimal regional reactivation configuration will be developed.

REGIONAL REACTIVATION

Granular activated carbon (GAC) is recognized as an effective technique for removing synthetic organics from both ground and surface waters. Questions have been raised, however, over the cost of using GAC in this manner. This issue is of particular concern to small water utilities because of the high unit costs associated with discarding spent carbon or reactivating it on-site. Regionalization is often proposed as a possible solution for minimizing these system costs. In this paper the cost tradeoffs associated with developing a regional reactivation system for Granular Activated Carbon (GAC) are discussed.

Previous EPA reports have presented a cost evaluation of the full-scale GAC treatment research facilities at the Cincinnati Water Works and Manchester Water Works.[11] These reports also presented cost estimates for various GAC treatment scenarios in order to examine the effect of economies of scale inherent in GAC systems, and the cost tradeoffs among individual GAC adsorption and on-site reactivation alternatives. The primary focus of that cost estimating effort was to examine the costs of GAC treatment systems consisting of steel or concrete GAC contactors and on-site reactivation using fluid-bed, infrared, and multihearth technologies. Overall costs associated with the reactivation process were found to contribute approximately 50 to 75% of the total cost of the GAC treatment system (the adsorption process contributes to the remaining portion of the total cost). As a solution to reducing the cost of the GAC reactivation process for a given treatment system, the concept of regional GAC reactivation was introduced.

Of particular interest was another supplimentary study conducted in Manchester designed to examine the feasibility of regional reactivation on a case study basis. That study is described briefly in Appendix B.

Cost equations were developed using preliminary cost estimating functions developed by the Drinking Water Research Division (DWRD) of EPA and then modified based on field scale research studies.[12,13,14] An optimization approach using cost equations was developed to find the "minimum cost" GAC reactivation strategy on a regional basis, by considering many alternative system components simultaneously. This approach consists of a mathematical model of the regional reactivation problem, structured as a mixed-integer program, and utilizes an efficient branch and bound solution procedure. The cost equations are discussed in Appendix C.

The following types of cost evaluations are made in this paper:

a. examination of the cost tradeoffs between on-site reactivation and replacement of spent carbon with virgin GAC;

b. examination of the cost tradeoffs among fluid bed, infrared, and multihearth GAC reactivation technologies;

c. examination of the cost tradeoffs between on-site reactivation by individual water utilities and participation in a regional reactivation system.

The regional GAC reactivation alternative involves two or more water utilities sharing the use of a common reactivation facility, and includes off-site carbon transport associated with the participating utilities, not located at the reactivation facility site.

DEVELOPMENT OF OPTIMIZATION MODEL

OBJECTIVE OF THE MODEL

A mathematical model that describes the GAC reactivation problem on a regional basis is developed in this section. The model is structured as a mathematical program and used to find cost-effective regional reactivation scenarios. The program consists of an objective function (criterion equation) which is to be optimized (minimized) subject to a set of constraints (equality and inequality equations).

When the criterion equation and the constraint equations are linear expressions, the problem is a linear programming problem. In this study, the objective function is not a linear expression by nature. Therefore, linear programming techniques, alone, cannot be used to solve the problem.[12]

ASSUMPTIONS

The general assumptions and conditions of the model are as follows:

1. The model represents the regional GAC reactivation system in a single planning period (i.e., the model represents a static view of the system).

2. The following parameters of the system are considered constant in a single period:

   a. the capital and O&M costs associated with the GAC reactivation process;

   b. the capital and O&M costs associated with off-site carbon transport;

   c. the amount of spent carbon generated by each water utility;

   d. the amount of carbon loss as a result of reactivation and handling;

   e. the upper and lower operating limits on the reactivation alternatives.

3. The design size of a reactivation furnace equals the amount of carbon allocated to the furnace, plus any excess capacity incorporated in the design to allow for furnace downtime. For example, if 3,650,000 pounds/year of carbon is allocated to a fluid bed furnace with an anticipated up-time factor of 70% then the furnace design size is determined to be 3,650,000/(365 * .7) = 14,285 pounds/day.

4. All carbon reactivated by a common furnace experiences the same carbon loss rate in that facility. However, the general model can be customized to handle variations in loss rates at a facility.

5. It is assumed that the concave cost functions can be closely approximated by piecewise linear segments.

MODEL NOTATION

The following are decision variables included in the mathematical model:

X_{ij} = the amount of GAC that a water utility at site i is to have reactivated at site j (pounds/year). Also, the amount of carbon transported if off-site reactivation is used.

W_{rj} = the amount of carbon to be reactivated using reactivation alternative, r, at site j (pounds/year). A reactivation alternative, r, represents a unique reactivtion device which has an upper limit on the amount of carbon that may be reactivated and a lower limit on the amount that must be reactivated if the alternative is developed.

Y_{rj} = zero-one bounded integer variable that brings into the solution the fixed charge associated with reactivation alternative, r, at site j, if r is developed at site j.

Q_{ij} = zero-one bounded integer variable which ensures that a water utility ships all or none of its GAC from site i to site j.

The following are the objective function coefficients included in the mathematical model:

C_{ij} = the unit transportation cost associated with shipping GAC from site i to site j ($/pound, return trip is included), carbon makeup costs associated with off-site transport carbon loss are included in the transportation cost;

O_{rj} = the variable (unit) component of the operating cost associated with alternative, r, at site j ($/pound), carbon makeup costs associated with the reactivation facility are included;

G_{rj} = the fixed charge component of the operating cost associated with alternative, r, at site j ($/year), carbon makeup costs associated with the reactivation facility are included;

K_{rj} = the variable (unit) component of the amortized capital cost associated with alternative, r, at site j ($/pound);

F_{rj} = the fixed charge component of the amortized capital cost associated with alternative, r, at site j ($/year).

The following are the constraint parameters included in the mathematical model:

D_i = the amount of GAC the utility at site i required to be reactivated (pounds/year);

U_{rj} = the upper limit (capacity) on the amount of carbon that may be reactivated by reactivation alternative, r, at site j (pounds/year);

L_{rj} = the lower limit on the amount of carbon that must be reactivated by reactivation alternative, r, at site j (pounds/year) if alternative r, is developed.

The following are system parameters included in the mathematical model:

n = the number of water utilities in the system;

m = the number of potential reactivation sites considered in the problem;

s = the number of reactivation alternatives considered (the same set of reactivation alternatives is considered at each potential reactivation site);

Z = the total cost of the reactivation strategy.

CRITERION FUNCTION

The objective function of the mathematical program represents the summation of all the cost components considered in the model. The objective function is to be minimized subject to the modeled constraints. In the solution to the mathematical program, the value of the objective function represents the total cost of the most economical regional reactivation strategy. The types of components considered in the objective function are: 1) the cost of GAC transport alternatives, 2) the amortized capital cost of reactivation alternatives, and 3) the O&M cost of reactivation alternatives.

GAC treatment costs include the capital and O&M expenses associated with loading, unloading, and hauling carbon to and from reactivation facilities, and also includes GAC makeup costs associated with off-site transport losses. The transport costs are assumed to be linear in nature, and require no special manipulation in modelling. The reactivation process capital and O&M costs are concave in nature and must be approximated by piecewise linear segments in the model. Figure 2 illustrates the approximation of a concave function by three piecewise linear segments. In this illustration, a reactivation alternative is associated with each linear segment. For example, the costs associated with operating alternative 3, $W_{3,1}$, include a variable cost of $O_{3,1}$ and a fixed charge of $G_{3,1}$. The model must be constructed so that these costs are assessed only if the alternative is developed. Also, since a piecewise linear segment is valid only between its lower limits, L_{rj}, and upper limit, U_{rj}, appropriate constraints must be constructed to ensure that the reactivation alternative associated with the piecewise segment is developed to operate at a level between L_{rj} and U_{rj}.

The mathematical structure of the objective function is as follows:

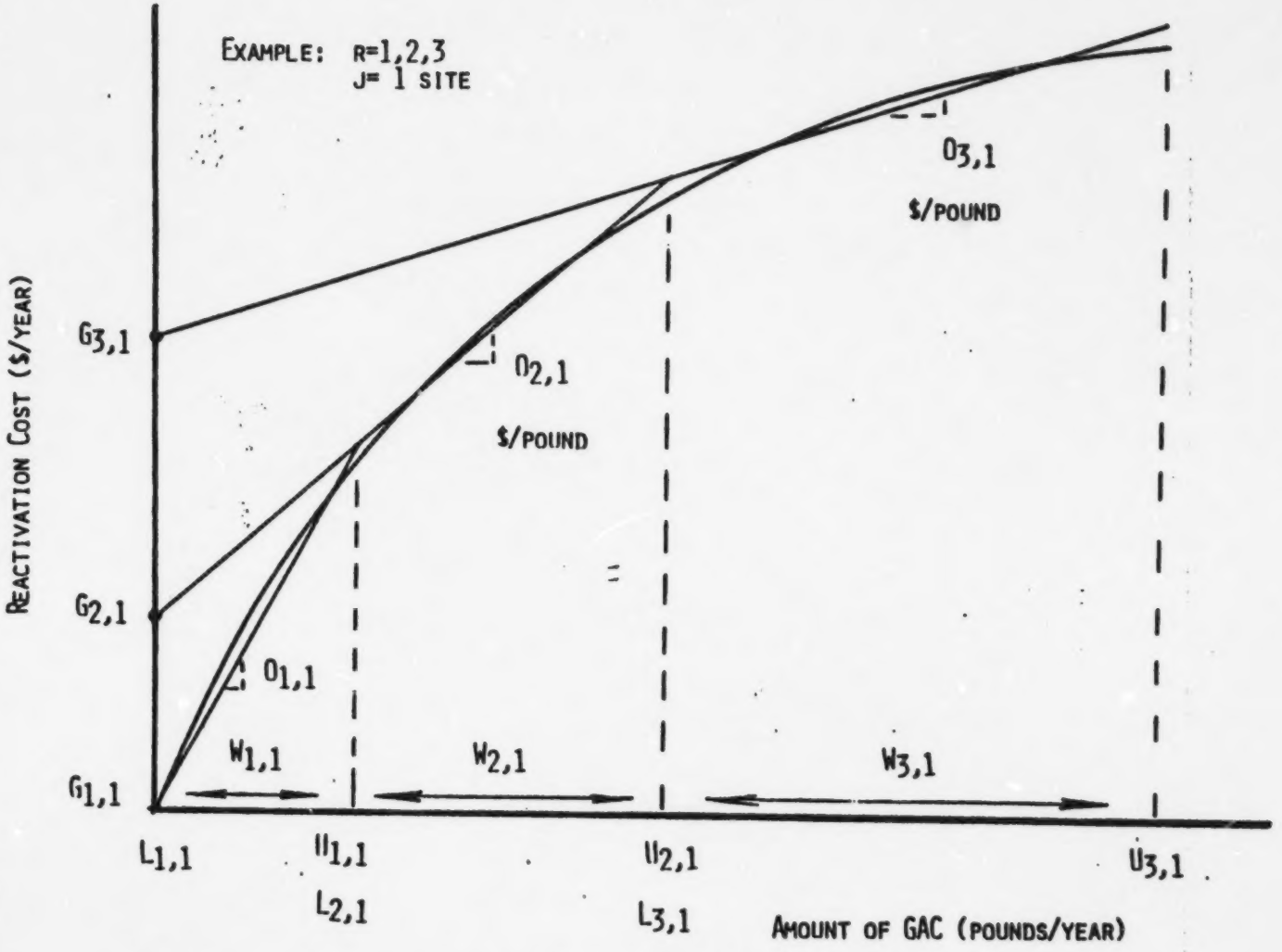

FIGURE 2 APPROXIMATION OF A CONCAVE FUNCTION BY PIECEWISE LINEAR SEGMENTS

$$\text{Minimize } Z = \sum_{j=1}^{m} \sum_{i=1}^{n} C_{ij} X_{ij} +$$

$$\sum_{r=1}^{s} \sum_{j=1}^{m} O_{rj} W_{rj} + \sum_{r=1}^{s} \sum_{j=1}^{m} G_{rj} Y_{rj} +$$

$$\sum_{r=1}^{s} \sum_{j=1}^{m} K_{rj} W_{rj} + \sum_{r=1}^{s} \sum_{j=1}^{m} F_{rj} Y_{rj} \qquad (1)$$

where

$\sum_{j=1}^{m} \sum_{i=1}^{n} C_{ij} X_{ij}$ = the total transportation cost of the system ($/year); (2)

$\sum_{r=1}^{s} \sum_{j=1}^{m} O_{rj} W_{rj} + \sum_{r=1}^{s} \sum_{j=1}^{m} C_{rj} Y_{rj}$ = the total reactivation O&M cost of the system ($/year) (3)

$\sum_{r=1}^{s} \sum_{j=1}^{m} K_{rj} W_{rj} + \sum_{r=1}^{s} \sum_{j=1}^{m} F_{rj} Y_{rj}$ = the total reactivation amortized capital cost of the system ($/year) (4)

DECISION VARIABLES

The mathematical program is optimized to obtain the minimum or near minimum cost solution to the problem. The solution gives the computed utilization level for each decision variable as directed by the minimum cost strategy. The following decision information is obtained from the model solution:

1) X_{ij}, (pounds/year), the amount of carbon from utility at i reactivated at site j. Also, the off-site transport specification.
2) Y_{rj}, the type(s) of reactivation furnace(s), if any, that should be developed at each site;
3) W_{rj}, (pounds/year), the amount of carbon to be reactivated the furnace(s) developed at each reactivation site;

4) the water utilities that will use common reactivation facilities, based on X_{ij}.

CONSTRAINTS

The mathematical model includes problem constraints in the form of linear expressions. The purpose of the constraints is to ensure that specified conditions are met in the problem solution.

The first constraint ensures that all of the spent carbon belonging to each water utility is assigned a reactivation site. This constraint is in response to meeting the reactivation demand of each water utility. Each water utility is permitted to transport GAC to any of the potential reactivation sites. This constraint is expressed as follows:

$$\sum_{j=1}^{m} X_{ij} = D_i \quad \text{for all } i = 1,\ldots,n \tag{5}$$

Each reactivation alternative has an upper limit on the amount of carbon that it may reactivate. This is the expected capacity of the furance alternative and the upper limit for the piecewise linear segment associated with the alternative. The following expression ensures that the furnace capacity constraint is met:

$$W_{rj} - U_{rj}\, Y_{rj} \leq 0 \quad \text{for all } r = 1,\ldots,s;\ j = 1,\ldots,m \tag{6}$$

The decision variable, Y_{rj}, is a zero-one bounded integer variable. If Y_{rj} is equal to 1, then the alternative, W_{rj}, is developed and constrained to be less than or equal to the specified capacity, U_{rj}. If Y_{rj} equals 0, then W_{rj} is constrained to be equal to zero and the alternative is not developed. This constraint also brings into the solution the fixed charge associated with the reactivation alternative, if the alternative is developed.

Similarly, each reactivation alternative has a lower limit on the amount of carbon that it must reactivate if the alternative is developed. This is the lower limit for the piecewise linear segment associated with the furnace alternative. The following expression ensures the lower limit constraint on reactivation alternatives:

$$W_{rj} - L_{rj} Y_{rj} \geq 0 \qquad \text{for all } r = 1,\ldots,s;\ j = 1,\ldots,m \tag{7}$$

If Y_{rj} equals 1, then the alternative, W_{rj}, is developed and constrained to be greater than or equal to the lower limit, L_{rj}. If Y_{rj} equals 0, then the alternative is not developed as constrained by expression (6).

Another important constraint that must be included in the model is the requirement to ensure that all carbon shipped to a reactivation site be reactivated by a device on the site and then shipped back to the various utilities from which it was sent. This requirement is met by the following expression.

$$\sum_{i=1}^{n} X_{ij} - \sum_{r=1}^{s} W_{rj} = 0 \qquad \text{for all } j = 1,\ldots,m \tag{8}$$

This constraint is known as the Kirchhoff Node Law. It ensures flow conservation; that is, the total flow into a node must equal the total flow out of the node. For a regional GAC reactivation scenario it requires that the total amount of carbon shipped to a reactivation site be equal to the total amount of carbon that is reactivated using all the furnaces on the site. Also, this constraint requires that furnaces be developed at such a size so that the sum of the operational capacities of the furnaces on a reactivation site (taking into account downtime) is equal to the amount of carbon shipped to that site.

It may be required that a water utility must ship all of its carbon to only one of the selected reactivation site, i.e., a utility may not split its carbon load and ship part of the carbon to one of the reactivation sites, and the other part to a different reactivation site. If this requirement is necessary then the following expression should be included in the mathematical model:

$$X_{ij} - D_i Q_{ij} = 0 \quad \text{for all } j=1,\ldots, \tag{9}$$

The variable Q_{ij}, is a zero-one bounded integer variable. If Q_{ij} equals 1, then all of the carbon at site i is shipped to site j. If Q_{ij} equals 0, then no carbon is shipped from site i to site j. The variable, Q_{ij}, has a cost coefficient of zero; therefore, it has been excluded from the objective function.

The mathematical program requires that all decision variables be non-negative. Therefore, the following constraints are included in the mathematical model:

$$X_{ij} \geq 0,\ W_{rj} \geq 0,\ Y_{rj} \geq 0,\ Q_{ij} \geq 0 \quad \text{for all } (i, j, r) \tag{10}$$

The mathematical program also requires that certain decision variables must take on integer values of 0 or 1. Therefore, the following constrant is included in the mathematical model:

Y_{rj} and Q_{ij} must be zero-one bounded integers (11)

The mathematical program developed in this section is called a mixed-integer program because some variables may take on fractional values while other variables must take on integer values.

COMPLETE STATEMENT OF THE PROBLEM

$$\text{Minimize } Z = \sum_{j=1}^{m} \sum_{i=1}^{n} C_{ij} X_{ij} + \sum_{r=1}^{s} \sum_{j=1}^{m} O_{rj} W_{rj} \sum_{r=1}^{s} \sum_{j=1}^{m} G_{rj} Y_{rj} +$$

$$\sum_{r=1}^{s} \sum_{j=1}^{m} K_{rj} W_{rj} + \sum_{r=1}^{s} \sum_{j=1}^{m} F_{rj} Y_{rj} \qquad (12)$$

subject to:

$$\sum_{j=1}^{m} X_{ij} = D_i \qquad \text{for all } i=1,\ldots,n \qquad (13)$$

$$W_{rj} - U_{rj} Y_{rj} \leq 0 \qquad \text{for all } r=1,\ldots,s;\ j=1,\ldots,m \qquad (14)$$

$$W_{rj} - L_{rj} Y_{rj} \geq 0 \qquad \text{for all } r=1,\ldots,s;\ j=1,\ldots,m \qquad (15)$$

$$\sum_{i=1}^{n} X_{ij} - \sum_{r=1}^{s} W_{rj} = 0 \qquad \text{for all } j=1,\ldots,m \qquad (16)$$

$$X_{ij} - D_i Q_{ij} = 0 \qquad \text{for all } j=1,\ldots,m;\ i=1,\ldots,n \qquad (17)$$

$$X_{ij} \geq 0\ W_{rj} \geq 0\ Y_{rj} \geq 0\ Q_{ij} \geq \qquad \text{for all } (i,j,r) \qquad (18)$$

Y_{rj} and Q_{ij} are (0,1) integer variables (19)

The technique used to solve this mathematical program is called a Branch and Bound procedure.

LIMITATIONS

The mathematical model represents a static view of the regional GAC reactivation scenario. Since a single time period is considered, reactivation demands and component costs must be assumed constant in the planning period. In reality, these parameters may vary over time. Therefore, it may be necessary to shorten the planning interval, so as to reduce the

significance of the variations in the model parameters. Also, since the model does not consider multiple time intervals, it limits the number of alternative strategies that can be considered in the long-term planning of regional GAC reactivation system.

DATA REQUIRED FOR THE STUDY

The following data is required in order to construct a mixed-integer problem in this study:

1. a set of the water utilities considered and their locations;
2. a set of the potential reactivation locations;
3. the travel distance (miles) from each water utility to each potential reactivation site;
4. the projected reactivation demand of each water utility;
5. carbon losses associated with transportation and reactivation facilities;
6. the cost parameters assumed in the capital and O&M functions associated with the reactivation process and off-site carbon transport;
7. a list of reactivation furnace alternatives to be considered and their upper and lower operating limits.

CASE STUDY EXAMPLE

An example of the use of the mathematical model and solution procedures is presented here. Consider the study area shown in Figure 3. Twenty water utilities in the Ohio River Valley are considered in this hypothetical problem. In this example, each of the twenty water utility locations is considered a potential location for reactivation facilities. No other reactivation sites are considered. Each utility can reactivate carbon on-site or ship carbon to any of the other nineteen sites. This

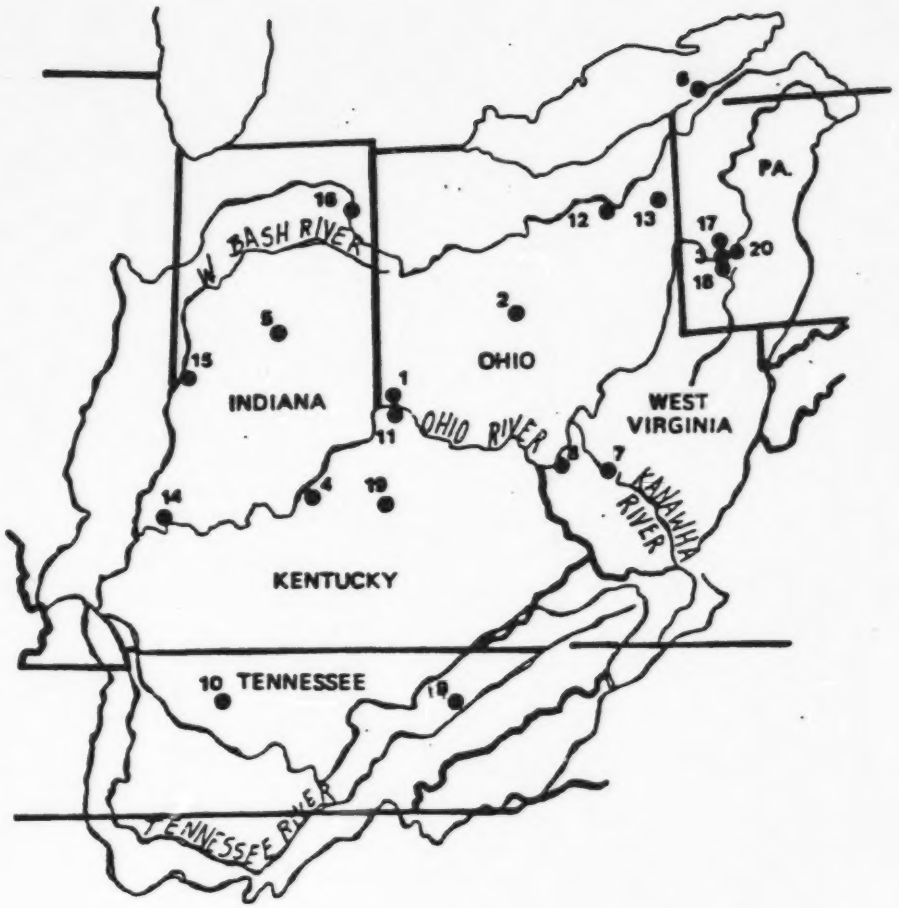

FIGURE 3 DIAGRAM OF OHIO RIVER VALLEY PROBLEM

means there are 400 feasible transportation alternatives to consider in the problem. Table 1 lists the reactivation demand of each water utility in this example. Three variations to the problem are considered, and a mixed-integer program is constructed and solved for each scenario.

TABLE 1. REACTIVATION DEMANDS IN OPTIMIZATION EXAMPLE

Site	Demand (pounds/year)	Site	Demand (pounds/year)
01	21,570,000	11	1,510,000
02	16,024,000	12	7,658,000
03	9,862,000	13	6,472,000
04	19,722,000	14	4,314,000
05	16,486,000	15	1,618,000
06	6,842,000	16	4,930,000
07	4,776,000	17	4,238,000
08	2,542,000	18	11,956,000
09	4,946,000	19	4,622,000
10	9,862,000	20	5,824,000
		TOTAL	165,774,000

SCENARIO 1

Scenario 1 is concerned with finding the minimum cost GAC reactivation scheme for the Ohio River Valley problem. The reactivation alternatives "r" considered in this problem are listed in Table 2, along with the corresponding model parameters.

TABLE 2. REACTIVATION ALTERNATIVES IN SCENARIO 1

r	Furnace Type	($/pound) $O_{rj} + K_{rj}$	($/year) $G_{rj} + F_{rj}$	(pounds/year) U_{rj}	(pounds/year) L_{rj}
1	M	.0233	416855	45,625,000	18,250,000
2	F	.0106	269990	21,900,000	10,950,000
3	F	.0172	197914	10,950,000	3,285,000
4	I	.0776	0	3,285,000	0

NOTE: M = multihearth, F = fluidized bed, I = infrared

Each alternative "r" represents a single furnace that may be developed at each potential reactivation site. In the model, the furnace must be developed to operate at a fixed level selected from the operating range U_{rj} to L_{rj}. The cost components associated with a furnace include the fixed charge ($G_{rj} + F_{rj}$) and the unit cost component ($O_{rj} + K_{rj}$). In this problem, all costs are expressed in terms of 1980 dollars, and GAC makeup costs are excluded. A list of the costs associated with the 400 transportation alternatives has been excluded in this paper because of space limitations. The mathematical program for scenario 1 excludes constraining expression (17) of the mathematical model. This permits water utilities to transport part of its carbon to one site and transport another part of its carbon to a different site, if it is most cost-effective.

The mixed-integer program in scenario 1 has the following problem statistics:

560 decision variables

740 total program variables

80 decision variables are integer

180 constraints

The mixed-integer program was optimized using the IBM MPSX/370, MIP/370 computer software package.[15,16] The global optimum (the proven best model solution) was obtained in a computer run-time of 3.37 CPU minutes. The best solution obtained is presented in Tables 3 and 4. These tables present the regional development plan of reactivation and the regional carbon distribution plan, i.e., which utility ships its carbon to which site. The plan calls for the development of a single large fluid bed furnace at sites 1, 2, 3, 4, 5, 10, 13, and 18, and for utilities in groups of two, three, and four to share the use of common reactivation facilities. In the search for the optimal solution, three other very good solutions were obtained, the worst of which has only a 2.2% higher total costs than the best solution. Table 5 presents a comparison of the facility development plans for the four solutions. The information presented in Table 5 is significant in that it shows there are several alternative regional strategies that are cost-effective.

TABLE 3. REGIONAL REACTIVATION FURNACE DEVELOPMENT PLAN IN SCENARIO 1

Site	Type	(pounds/day) Design Size	Furnaces	(pounds/year) Operating Level
1	F	84000.00	1	21,900,000
2	F	84000.00	1	21,900,000
3	F	57388.00	1	14,962,000
4	F	84000.00	1	21,900,000
5	F	84000.00	1	21,900,000
10	F	74457.00	1	19,412,000
13	F	84000.00	1	21,900,000
18	F	84000.00	1	21,900,000

NOTE: M = multihearth, I = infrared, F = fluidized bed

TABLE 4. REGIONAL GAC DISTRIBUTION PLAN IN SCENARIO 1

Distribution of Carbon	Amount (pounds/year)	Distribution of Carbon	Amount (pounds/year)
Utility 01 to site 01	21,570,000	Utility 09 to site 10	4,946,000
Utility 11 to site 01	330,000	Utility 10 to site 10	9,862,000
Utility 02 to site 02	160,024,000	Utility 14 to site 10	4,314,000
Utility 08 to site 02	2,542,000	Utility 19 to site 10	290,000
Utility 11 to site 02	1,180,000	Utility 06 to site 13	6,636,000
Utility 19 to site 02	2,154,000	Utility 12 to site 13	7,658,000
Utility 03 to site 03	9,862,000	Utility 13 to site 13	6,472,000
Utility 06 to site 03	206,000	Utility 16 to site 13	1,134,000
Utility 17 to site 03	4,238,000	Utility 07 to site 18	4,776,000
Utility 20 to site 03	656,000	Utility 18 to site 18	11,956,000
Utility 04 to site 04	19,722,000	Utility 20 to site 18	5,168,000
Utility 19 to site 04	2,178,000		
Utility 05 to site 05	16,486,000	TOTAL	165,774,000
Utility 15 to site 05	1,618,000		
Utility 16 to site 05	3,796,000		

TABLE 5. COMPARISON OF FACILITY DEVELOPMENT PLANS FOR FOUR SOLUTIONS IN SCENARIO 1

Site	r	2.2% higher than best	.5% higher than best	.002% higher than best	best
01	2	X		X	X
02	2	X	X	X	X
03	2		X	X	X
04	2	X	X	X	X
05	2	X	X	X	X
10	2	X	X	X	X
11	2		X		
12	2			X	
13	2	X	X		X
18	2	X	X	X	X
18	3	X			
07	4	X			

NOTE: See Table 2 for identification of r values.

SCENARIO 2

Scenario 2 differs from Scenario 1 only by the set of reactivation alternatives used in the mixed-integer program. The fluid bed alternatives are excluded in Scenario 2 in order to find the best scheme using only multihearth and/or infrared devices. The reactivation alternatives and corresponding model parameters are presented in Table 6. The mixed-integer program in Scenario 2 has the following problem statistics:

520 decision variables

660 total variables

60 variables are integer

140 constraints

The global optimum was obtained in a program run-time of 1.01 CPU minutes. the optimal solution is presented in Tables 7 and 8. Table 7 presents the regional reactivation furnace development plan which calls for the development of a large multihearth furnace at sites 1, 2, 4 and 18. Table 8 presents the assignments of water utilities to reactivation facilities. The plan calls for utilities to share the use of common reactivation facilities in groups of five and six.

TABLE 6. REACTIVATION ALTERNATIVES IN SCENARIO 2

r	Furnace Type	($/pound) $O_{rj} + K_{rj}$	($/year) $G_{rj} + F_{rj}$	(pounds/year) U_{rj}	(pounds/year) L_{rj}
1	M	.0233	416855	45,625,000	18,250,000
2	M	.0309	278083	18,250,000	9,125,000
3	I	.0615	0	9,125,000	0.0

NOTE: M = multihearth, F = fluidized bed, I = infrared

TABLE 7. REGIONAL REACTIVATION FURNACE DEVELOPMENT PLAN IN SCENARIO 2

Site	Type	(pounds/day) Design Size	No. of Furnaces	(pounds/year) Operating Level
1	M	175000.00	1	45,625,000
2	M	117250.00	1	30,569,000
4	M	168595.00	1	43,955,000
18	M	175000.00	1	45,625,000

NOTE: M = multihearth, I = infrared, F = fluidized bed

TABLE 8. REGIONAL GAC DISTRIBUTION PLAN IN SCENARIO 2

Distribution of Carbon	Amount (pounds/year)	Distribution of Carbon	Amount (pounds/year)
Utility 01 to site 01	21,570,000	Utility 09 to site 04	4,946,000
Utility 05 to site 01	16,486,000	Utility 10 to site 04	9,862,000
Utility 11 to site 01	1,510,000	Utility 14 to site 04	4,314,000
Utility 15 to site 01	1,129,000	Utility 15 to site 04	488,000
Utility 16 to site 01	4,930,000	Utility 19 to site 04	4,622,000
Utility 02 to site 02	16,024,000	Utility 03 to site 18	9,862,000
Utility 06 to site 02	6,842,000	Utility 12 to site 18	7,272,000
Utility 07 to site 02	4,776,000	Utility 13 to site 18	6,472,000
Utility 08 to site 02	2,542,000	Utility 17 to site 18	4,238,000
Utility 12 to site 02	385,000	Utility 18 to site 18	11,956,000
Utility 04 to site 04	19,722,000	Utility 20 to site 18	5,824,000
		TOTAL	165,774,000

SCENARIO 3

The purpose of Scenario 3 is to obtain a cost-effective solution to the problem defined in Scenario 1 with the requirement that water utilities may not split its shipment of GAC, transporting a portion to one site and transporting another portion to a different site. This requirement is accomplished

by including expression (17) of the mathematical model in the mixed-integer program. The reactivation alternatives used in Scenario 3 are presented in Table 9. The mixed-integer program in Scenario 3 has the following problem statistics:

920 decision variables

1460 total variables

460 variables are integer

540 constraints

The mixed-integer program was optimized to near global optimality. The best solution obtained has a functional value that is no more than 7% higher than the functional value of the global optimum. The best solution was proven to be no worse than 7% from the global optimum in a program run-time of 9.30 CPU minutes. Tables 10 and 11 present the best solution obtained in Scenario 3. Table 10 gives the regional furnace development plan, which calls for a large fluid bed furnace at sites 1, 2, 3, 4, 5, 10, 13, and 20, and a small infrared furnace at site 4. Table 11 presents the assignments of water utilities to reactivation facilities. The plan calls for utilities to share the use of common regional facilities in group sizes of two, three, and four. Each utility ships all of its carbon to one of the eight reactivation sites. In the search for the optimal solution another good scheme was found. The solution has only a 7% higher cost than the best solution obtained. Table 12 presents a comparison of facility development plans for the two solutions.

TABLE 9. REACTIVATION ALTERNATIVES IN SCENARIO 3

r	Furnace Type	($/pound) $O_{rj} + K_{rj}$	($/year) $G_{rj} + F_{rj}$	(pounds/year) U_{rj}	(pounds/year) L_{rj}
1	F	.0106	269990	21,900,000†	10,950,000
2	F	.0172	197914	10,950,000	3,285,000
3	I	.0776	0	3,285,000	0.0

NOTE: M = multihearth, F = fluidized bed, I = infrared

†An exception is $U_{1,1}$ = 23,360,000

TABLE 10. REGIONAL REACTIVATION FURNACE DEVELOPMENT PLAN IN SCENARIO 3

Site	Type	(pounds/day) Design Size	Furnaces	(pounds/year) Operating Level
1	F	88526.00	1	23,080,000
2	F	79190.00	1	20,646,000
3	F	83685.00	1	21,818,000
4	F	84000.00	1	21,900,000
5	F	82143.00	1	21,416,000
10	F	79550.00	1	20,740,000
13	F	80440.00	1	20,972,980
20	F	56912.00	1	14,837,980
4	I	1395.00	1	363,905

NOTE: M = multihearth, I = infrared, F = fluidized bed

TABLE 11. REGIONAL GAC DISTRIBUTION PLAN IN SCENARIO 3

Distribution of Carbon	Amount (pounds/year)
Utility 01 to site 01	21,570,000
Utility 11 to site 01	1,510,000
Utility 02 to site 02	16,024,000
Utility 19 to site 02	4,622,000
Utility 03 to site 03	9,862,000
Utility 18 to site 03	11,956,000
Utility 04 to site 04	19,722,000
Utility 08 to site 04	2,542,000
Utility 05 to site 05	16,486,000
Utility 16 to site 05	4,930,000
Utility 09 to site 10	4,946,000
Utility 10 to site 10	9,862,000
Utility 14 to site 10	4,314,000
Utility 15 to site 10	1,618,000
Utility 06 to site 13	6,842,000
Utility 12 to site 13	7,658,000
Utility 13 to site 13	6,472,000
Utility 07 to site 20	4,776,000
Utility 17 to site 20	4,238,000
Utility 20 to site 20	5,824,000
TOTAL	165,774,000

TABLE 12. COMPARISON OF FACILITY DEVELOPMENT PLANS FOR TWO SOLUTIONS IN SCENARIO 3

Site	r	Functional: 7% higher than best	Functional: Best
01	1	X	X
02	1	X	X
03	1		X
04	1	X	X
05	1	X	X
10	1	X	X
13	1	X	X
20	1	X	X
19	2	X	
02	3	X	
04	3		X
13	3	X	
19	3	X	

EFFICIENCY OF PROCEDURE

Table 13 presents a summary of the computational experience with the three sample problems. The mixed-integer programs were optimized using the MPSX/370, MIP/370 (realse 1.5) software and run on on Amdahl 470/V6 digital computer. The computer run-time recorded for each program is very good, considering the size of each problem. The results shown in Table 13 demonstrate that the solution procedure is computationally efficient.

SUMMARY AND CONCLUSIONS

Regionalization of GAC reactivation facilities provides an opportunity for minimizing the costs of reactivating Granular Activated Carbon. High unit costs for reactivation are of particular concern to small utilities. A field research study was conducted with the Manchester, NH water works to examine the concept of regional GAC reactivation. Regional reactivation proved to be cheaper for the participating utilities when compared against the costs for replacement of spent carbon with virgin GAC and estimated costs for on-site reactivation. The effect of economies of scale was demonstrated by this project, and small utilities clearly benefitted from participating in a regional system. In general, the cost effectiveness of regional reactivation must be evaluated on a case by case basis because of the many variables and parameters affecting costs and the interdependencies among participating water utilities in a regional scenario.

Cost equations have been developed and modified using information obtained from field scale research studies. These equations are presented in this paper, in order to provide one with a means of generating cost estimates and evaluating GAC reactivation strategies using design and cost parameters applicable to one's particular case.

TABLE 13. SUMMARY OF COMPUTATIONAL EXPERIENCE

Problem	No. of Decision Variables	(Columns) No. of Total Variables	No. of Integer Variables	(Rows) No. of Constraints	No. of Nodes Generated†	Global Optimality	CPU TIME†† (minutes)	Overall††† Regional System Cost ($/year)
1	560	740	80	180	1363	proven	3.37	15,145,758
2	520	660	60	140	366	proven	1.01	17,155,994
3	920	1460	460	540	1649	within 7%	9.30	15,210,087

†Number of branching nodes (subproblem optimizations) generated in the branch and bound procedure.

††Optimization performed by MPSX/370, MIP/370 on an Amdahl 470/V6 computer.

†††Based on 1980 costs.

An optimization approach that utilizes cost equations has been developed to aid one in finding the "minimum cost" GAC reactivation strategy on a regional basis. The approach presented in this paper consists of a mathematical model of the regional reactivation problem, structured as a mixed-integer program, and utilizes an efficient branch and bound solution procedure.

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APPENDIX A - NOTATION

CC = construction cost, $

AC = amortized capital cost, $/year

a,b,c...t,u = equation coefficients and exponent

USRT = design variable

NU = number of reactivators

CCI = ENR construction cost index, base year 1913

OHEF = overhead, interest during construction, engineering fee in $ (must be added separately)

I = period interest rate (decimal)

N = payback period, years

PE = process electrical cost in $/yr

BE = building electrical cost in $/yr

MAINT = maintenance materials cost for reactivators

MAINTO= maintenance materials cost for off-site GAC transport in $/yr

LABOR = process O&M labor cost in $/yr

LABORO= labor cost for off-site GAC transport in $/yr

FUELN = process natural gas cost in $/yr

FUELF = process fuel oil cost in $/yr

FUELO = full cost for off-site GAC transport in $/yr

MAKEUP= GAC makeup cost in $/yr when USRT is in lbs/yr

MILES = one-way GAC transport distance in miles

XLBS = lbs of carbon on which purchase cost is based

PPI = producers price index value

X_{ij} = the amount of GAC that a water utility at site i is to have reactivated at site j (pounds/year). Also, the amount of carbon transported if off-site reactivation is used.

W_{rj} = the amount of carbon to be reactivated using reactivation alternative, r, at site j (pounds/year). A reactivation alternative, r, represents a unique reactivation device which has an upper limit on the amount of carbon that may be reactivated and a lower limit on the amount that must be reactivated if the alternative is developed.

Y_{rj} = zero-one bounded integer variable that brings into the solution the fixed charge associated with reactivation alternative, r, at site j, if r is developed at site j.

Q_{ij} = zero-one bounded integer variable which ensures that a water utility ships all or none of its GAC from site i to site j.

C_{ij} = the unit transportation cost associated with shipping GAC from site i to site j ($/pound, return trip is included), carbon makeup costs associated with off-site transport carbon loss are included in the transportation cost;

O_{rj} = the variable (unit) component of the operating cost associated with alternative, r, at site j ($/pound), carbon makeup costs associated with the reactivation facility are included;

G_{rj} = the fixed charge component of the operating cost associated with alternative, r, at site j ($/year), carbon makeup costs associated with the reactivation facility are included;

K_{rj} = the variable (unit) component of the amortized capital cost associated with alternative, r, at site j ($/pound);

F_{rj} = the fixed charge component of the amortized capital cost associated with alternative, r, at site j ($/year);

D_i = the amount of GAC the utility at site i requires to be reactivated (pounds/year);

U_{rj} = the upper limit (capacity) on the amount of carbon that may be reactivated by reactivation alternative, r, at site j (pounds/year);

L_{rj} = the lower limit on the amount of carbon that must be reactivated by reactivation alternative, r, at site j (pounds/year) if alternative r, is developed;

n = the number of water utilities in the system;

m = the number of potential reactivation sites considered in the problem;

s = the number of reactivation alternatives considered (the same set of reactivation alternatives is considered at each potential reactivation site);

Z = the total cost of the reactivation strategy.

APPENDIX B

MANCHESTER REGIONAL REACTIVATION

Having achieved an initial objective of evaluating the performance and cost of a field-scale on-site fluid bed GAC reactivation system, future use of the facility at Manchester New Hampshire for providing regional reactivation service was investigated.[12] The fluid bed GAC reactivator at the Manchester Water Works (MWW) has a throughput capacity of approximately (500 pounds/hour) 3.6 milion pounds (1.63 million kg) of GAC per year, assuming a reasonable operating factor of about 75%. Based on this throughput it would take less than 4 months to reactivate the entire one million pounds of GAC at the MWW treatment plant, in any given year. The large excess capacity of the reactivator prompted MWW to explore the feasibility of providing off-site (regional) reactivation to the water utilities in the New England area. An initial regional reactivation effort was undertaken to evaluate the costs and performance of providing off-site reactivation to other utilities.

The first utility which participated in the regional program was the Connecticut Water Company, Kelseytown Treatment Plant located 172 miles (277 km) from MWW. This was followed by off-site reactivation for Danvers, MA Water Treatment Plant, and Lowell, MA Water Treatment Plant, located 41 and 33 miles (66 and 53 km) from MWW, respectively. All three utilities are conventional water treatment plants using GAC primarily for taste and odor removal.

A summary of the regional GAC reactivation unit costs for the three participating water utilities is given in Table B-1. The table presents for each utility: the unit total cost of regional reactivation service by MWW (including off-site GAC transport), an estimated unit cost for total spent carbon replacement with virgin GAC, and an estimated unit cost for on-site reactivation. The "virgin GAC replacement cost" refers to the estimated cost associated with the replacement of the entire 40,000 pounds (18,160 kg) of spent carbon for each utility. The virgin GAC replacement unit cost is lower than the unit cost of GAC makeup because of the economies of scale inherent in purchasing larger quantities of carbon (lower unit prices for larger quantities). The "on-site reactivation cost" refers to the estimated cost associated with a utility constructing and operating their own individual on-site reactivation facility. The on-site costs are based on the use of infrared reactivation and assume the following reactivation demands for the three utilities: 96,000 lbs/year (43,584 kg) for Connecticut Water Company; 90,000 lbs/year (40,860 kg) for Danvers, Mass.; and 250,000 lbs/year (113,500 kg) for Lowell, Mass.

Table B-1 clearly demonstrates the cost effectiveness of regional reactivation as compared to virgin replacement and on-site reactivation for the three participating utilities. The cost of regional reactivation service for the Connecticut Water Company was 66.24 ¢/lb (145.90 ¢/kg) versus complete virgin replacement at 100.7 ¢/lb (221.80 ¢/kg) and on-site reactivation at 138.7 ¢/lb (305.50 ¢/kg); for the Danvers Water Plant, regional reactivation was 37.50 ¢/lb (82.60 ¢/kg) versus replacement at 63.4 ¢/lb (139.64 ¢/kg) and on-site reactivation at 138.9 ¢/lb (305.95 ¢/kg); and for the Lowell Water Plant, regional reactivation was 44.95 ¢/lb (99.00 ¢/kg) versus

replacement at 100.5 ¢/lb (221.36 ¢/kg) and on-site reactivation at 77.3 ¢/lb (170.26 ¢/kg). The on-site reactivation alternatives were not cost effective because of the very high unit costs associated with small reactivation facilities and operations.

TABLE B-1. SUMMARY OF MANCHESTER WATER WORKS REGIONAL REACTIVATION COSTS (1981)

Utility	Regional Reactivation Cost ¢/lb	Estimated Virgin GAC Replacement Cost ¢/lb	Estimated On-Site Reactivation Cost ¢/lb
Connecticut Water Co.	66.24	100.7	138.7
Danvers, Mass.	37.50	63.4	138.9
Lowell, Mass.	44.95	100.5	77.3

*To convert from ¢/lb to ¢/kg divide by 0.454.

APPENDIX C

GAC REACTIVATION COST ESTIMATING EQUATIONS

The mathematical functions for the capital and O&M costs associated with GAC reactivation and off-site carbon transport are as follows:

Capital Cost

$$CC = [a+b(USRT)^{c}](NU)(CCI/2850.7) + (OHEF) \quad (C-1)$$

$$AC = (CC)\ (I(1+1)^{N}/[(1+I)^{N}-1] \quad (C-2)$$

O&M Costs

$$PE = [d+e(USRT)^{f}](NU)(\$/kwh) \quad (C-3)$$

$$BE = [g+h(USRT)^{i}](NU)(\$/kwh) \quad (C-4)$$

$$MAINT = [j+k(USRT)^{\ell}](PPI/199.7)(NU) \quad (C-5)$$

$$MAINTO = [j+k(USRT)^{\ell}(MILES)^{\ell\ell}](PPI/199.7) \quad (C-6)$$

$$LABOR = [m+n(USRT)^{o}](NU)(\$/hour) \quad (C-7)$$

$$LABORO = [m+n(USRT)^{o}(MILES)^{oo}](\$/hour) \quad (C-8)$$

$$FUELN = [p+q(USRT)^{r}](NU)(\$/ft^3) \quad (C-9)$$

$$FUELF = [p+q(USRT)^{r}](1/139)(NU)(\$/gallon) \quad (C-10)$$

$$FUELO = [p+q(USRT)^{r}(MILES)^{rr}](\$/gallon) \quad (C-11)$$

$$MAKEUP = [(XLBS)^{t}(USRT)^{u}](\$/lb) \quad (C-12)$$

where

- CC = reactivation construction cost, $
- AC = amortized capital cost, $/year
- PE = process electrical cost
- BE = building electrical cost
- MAINT = maintenance materials cost

MAINTO= maintenance material cost for off-site GAC transport

LABOR = process O&M labor cost

LABORO= O&M labor cost for off-site GAC transport

FUELN = process natural gas cost

FUELF = process fuel oil cost

FUELO = fuel costs for off-site transport

MAKEUP= carbon makeup cost in $/year when USRT is in pounds/year

a,b,c...t,u = equation coefficients and exponents given in Tables C-1 and C-2

USRT = design variable as defined in tables C-1 and C-2

NU = number of reactivation furnaces

CCI = ENR construction cost index, base year 1913

OHEF = overhead, interest during construction, engineering fees, $ (must be added separately)

I = period interest rate (decimal)

N = payback period, year

MILES = one-way distance in miles

XLBS = pounds of carbon on which the purchase cost ($/pound) is based

PPI = producers price index value

All O&M costs are in $/year and assume utilization 100% of the time. If a process is only used part of the time then the cost estimate should be adjusted according the the percent utilization.

The coefficients and exponents applicable to the Capital Cost functions are given in Table C-1. the O&M cost function coefficients are given in Table C-2.

TABLE C-2. O&M COST FUNCTION COEFFICIENTS AND EXPONENTS

Process Name	USRT RANGE	Model Value
Fluid Bed Reactivation	6,500-50,000 lbs/day	d=0; e=43.80; f=1.000; j=7232; k=385.19; ℓ=0.353; m=4000; n=245.0; o=0.450; p=111107; q=1046.14; r=1.008
Infrared Reactivation	2,400-60,000 lbs/day	d=44779; e=315.55; f=0.988; g=417; h=23.14 i=0.753; j=0; k=427.25; ℓ=0.397; m=4000; n=25.7; o=0.742
Multihearth Reactivation	27-1,510 ft^2	d=472706; e=8517.36; f=0.755; g=11246; h=312.08; i=0.649; j=0; k=846.15; ℓ=0.401; m=3000; n=604.0; o=0.728; p=366525 q=287714.93; r=0.899
Off-site GAC Transport (<25 miles)	30,000-3,000,000 lbs	j=0; k=2.31*10^{-5}; ℓ=0.992; ℓℓ=1.015; m=2.5; n=3.15*10^{-5}; o=1.067; oo=0.477; p=0; q=2.38*10^{-5} r=0.989; rr=0.984
Off-site GAC Transport (>25 miles)	30,000-3,000,000 lbs	j=0; k=2.16*10^{-5}; ℓ=1.001; ℓℓ=0.998; m=0 n=1.91*10^{-4}; o=1.021; oo=00.131; p=0; q=1.83*10^{-5} r=1.000; rr=1.012